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LAW OFFICES OF
JACOBSON HOLMAN
PROFESSIONAL LIMITED LIABILITY COMPANY
400 SEVENTH STREET, N. W.
WASHINGTON, D.C. 20004
(202) 638-6666

JACOBSON HOLMAN STERN
OF COUNSEL
MARVIN R. STERN
NATHANIEL A. HUMPHRIES
TELEFAX:
(202) 393-5350
(202) 393-5351
(202) 393-5352
E-MAIL: IP@JHIP.COM
INTERNET: WWW.JHIP.COM
*BAR OTHER THAN D.C.

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Alexandria, VA 22313-1450

Sir:

Transmitted herewith for filing is a PROVISIONAL APPLICATION of **Guillaume VIENNE** residing at **Kobenhavn V, Denmark** for **NUMERICAL APERTURE CONVERTING DEVICE, METHOD OF ITS PRODUCTION, AND USE THEREOF.** The application comprises a 25 -page specification and 9 sheets of drawings.

Accompanying this application for filing is:

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CORRESPONDENCE ADDRESS:

JACOBSON HOLMAN PLLC
400 Seventh Street, N.W.
Washington, D.C. 20004

Respectfully submitted,

JACOBSON HOLMAN PLLC

By Harvey B. Jacobson, Jr.
Harvey B. Jacobson, Jr.
Reg. No. 20,851

HBJ:mch

NUMERICAL APERTURE CONVERTING DEVICE, METHOD OF ITS PRODUCTION, AND USE THEREOF

TECHNICAL FIELD

The invention relates to an optical component in the form of a photonic crystal fibre for coupling light from one component/system with a given numerical aperture to another component/system with another numerical aperture. The invention further relates to methods of producing the optical component, and articles comprising the optical component, and to the use of the optical component. The present invention is based on properties of photonic crystal fibres (PCF).

The invention may e.g. be useful in applications such as fibre lasers or amplifiers, where light may be coupled efficiently from pump sources to a double clad fibre using the optical component.

BACKGROUND ART

Optical fibres are today used in numerous applications that span very diverse fields of optics. These fields include telecommunications, medicine, sensors, lasers, and many others. PCFs have recently emerged as an attractive class of fibres, where various properties may be tailored in new or improved manners compared to conventional (solid) optical fibers. PCFs are generally described by Bjarklev, Broeng, and Bjarklev in "Photonic crystal fibres", Kluwer Academic Press, 2003.

A common problem in fibre optics is to launch light into a fibre efficiently. Often the source of light and the fibre to couple into have different divergence angles (numerical aperture (NA)) and spot/core sizes. A specific problem is to launch light from a pump-diode-laser with a large spot size and relatively low numerical aperture into a double clad fibre laser with a small area and large numerical aperture.

The traditional method of solving this problem is to use bulk optics. This solution has a number of problems. One problem is related to difficulties in achieving coupling with low loss. Another problem is to achieve good coupling for a wide range of wavelengths. A third problem is mechanical stability. Fabrication of devices using bulk optics is also relatively complicated. Furthermore, reflection from the multiple glass surfaces may degrade performance of the system.

WO03019257 deals with optical waveguides, for which improved coupling into cladding pumped optical fibres may be obtained through optimal designs of micro-structured outer cladding regions that provide high NA for mode(s) of an inner cladding region. This is achieved by the use of low index cladding features with a relatively narrow area between neighbouring low-index features constituting an air-clad surrounding the inner cladding.

DISCLOSURE OF INVENTION

It is an object of the present invention to provide improved optical components and methods for coupling light into optical fibres.

It is an object of the present invention to provide an optical component that may transform light from one NA and core/spot size to another NA and core/spot size.

The numerical aperture (NA) is given by the divergence angle. For standard fibre, NA is given by the refractive index difference between the core and the cladding. For air-clad fibres, the NA is given by the core index and the specific geometry and material choice of the air-clad (as described in WO03019257). The larger the NA, the larger angle of incident light is guided by total internal reflection. Typically, NA of a waveguide is defined by: $NA=\sin(\theta)$, where θ is given as the FWHM or $1/e^2$ angle of the a light beam emitted from the waveguide.

This and other objects of the invention are achieved by the invention described in the accompanying claims and as described in the following.

An NA converting photonic crystal fibre

An object of the invention is achieved by a photonic crystal fibre comprising

a) a multi-mode core region for propagating light in a longitudinal direction of said photonic crystal fibre,

b) an air-clad region comprising a multitude of longitudinally extending spaced apart micro-structural elements surrounding said multi-mode core region,

the photonic crystal fibre comprising a first and a second end, wherein cross-sectional dimensions of said multimode core region and said air-clad region are reduced from said first end to said second end so that brightness is essentially conserved.

Brightness is defined as luminous flux emitted from a surface per unit solid angle per unit of area, projected onto a plane normal to the direction of propagation. In other words, the term brightness is in the present context taken to mean $B=P/(\Omega*A)$, where P is optical power, Ω is solid angle and A is area of emitted light from a facet. Brightness is also known as luminance and luminous sterance.

The term 'brightness is essentially conserved' is in the present context taken to mean that the ratio of the brightness at the first and second ends respectively is in the range from 60% to 100%, such as in the range from, 80% to 99%, 90% to 99%.

It is to be understood that in the present context, a 'photonic crystal fibre' may have cross sectional dimensions that are normal for a product to be termed an 'optical fibre', i.e. including outer cross sectional dimensions in the range hundred to several hundred μm range as well as larger dimensions such as in the mm range.

In the present context, the 'multi-mode core region' is defined - when viewed in a cross section perpendicular to a longitudinal direction of the fibre - as a (typically central) light-propagating part of the fibre. The multi-mode core region is limited in a radial direction by micro-structural elements of the air-clad region. The multi-mode core is typically used to guide pump light from one or more pump light sources to a double-clad fibre (standard or air-clad fibres are both of relevance), the double-clad fibre comprising one or more single- or few mode cores that comprise one or more rare earth dopants (active materials). Optionally, a photonic crystal fibre according to a preferred embodiment of the present invention may comprise a single- or few-mode core being surrounded by the multi-mode core. This may for example be preferred in order to combine a pump coupling fibre component and an active, air-clad optical fibre into one device. In current 'double clad fibre terminology' a 'multi-mode core' is sometimes termed an 'inner cladding' or 'a pump core'.

Advantages of having both a single- or few-mode core surrounded by a multi-mode core may also be that an optical device (comprising a PCF according to the invention) for example may be used to couple pump light into the multi-mode core, as well as to couple light from a single-mode seed or feed signal to the single- or few mode core, for example for seeding a short pulse air-clad fibre amplifier.

The term 'micro-structural elements' is in the present context taken to mean structural elements enclosed by a background material, the micro-structural elements having a different refractive index than said background material. A micro-structural element may e.g. be a hole or void or any other element enclosed in a background material having a refractive index different from that of the background material, e.g. of a fluid or solid material.

In an embodiment, the multitude of micro-structural elements constituting the air-clad comprises at least one ring of longitudinally extending micro-structural elements, a ring of micro-structural elements being interpreted as a group of elements located on an annular curve (e.g. a circular or elliptical curve), the elements being located on the curve being understood

as each element of the group constituting a ring of elements having their outer boundaries touching or intersecting the annular curve.

In an embodiment of the invention, the micro-structural elements of the air-clad comprise holes or voids. In an embodiment, a majority or all of the micro-structural elements of the air-clad are constituted by holes.

In an embodiment of the invention, the photonic crystal fibre has numerical aperture NA and maximum cross sectional dimension D of the multimode core region (e.g. the diameter of a substantially circular multimode core region) at said first and second ends NA_1, D_1 and NA_2, D_2, respectively.

With brightness generally defined as $B=P/(\Omega*A)$, $\Omega*A$ may be determined from NA*D. Hence, for a loss-less photonic crystal fibre according to an embodiment of the present invention, brightness conservation from the first end to the second end means $NA_1*D_1 = NA_2*D_2$. In practice, loss-free operation is not possible (due to many factors including material absorption, structural variations in raw materials, production-induced structural variations, etc.), and essential brightness conservation may be expressed as NA_1*D_1/NA_2*D_2 in the range from 0.5 to 1.5. The ratio may be smaller or larger than 1 depending on the exact structure at two ends of the optical fibre.

In an embodiment, the ratio of the product of the numerical aperture and the maximum cross sectional dimension at said first and second ends, NA_1*D_1/NA_2*D_2 is in the range from 0,5 to 1,5 such as from 0,8 to 1,2, such as from 0,9 to 1,1.

In an embodiment of the invention, the cross sectional dimensions of the multimode core region and the air-clad region are smaller at the second end than at the first and whereby it is achieved that the PCF has a larger NA at second (NA_2) end than at the first end (NA_1), and D_2 is smaller than D_1. The first end may serve as an input end for coupling light from a pump light source and the second end may be used to couple light to a double-clad fibre – for example an active, double-clad fibre. The second end may

alternatively be the end of an active, double-clad fibre being part of the NA converting optical fibre.

In an embodiment, the cross sectional dimensions of the PCF at the first end is larger than or around twice the corresponding dimensions at the second end, such as larger than or around three times, such as larger than or around 4 times, such as larger than or around 5 times the corresponding dimensions at the second end.

In an embodiment of the invention, the minimum boundary to boundary distance between neighbouring micro-structural elements of the air-clad in an annular direction – termed the bridge width - is denoted b. In an embodiment, the micro-structural elements of the air-clad are located on concentric rings and b is substantially constant for all elements of a particular ring. In an embodiment, the ratio of the maximum cross sectional dimension of the multimode core region to the minimum boundary to boundary distance between neighbouring elements of a ring of elements of the air-clad, D_i/b_i is substantially equal at the cross sections of the first and second ends of the PCF. In an embodiment of the invention, the ratio $(D_1/b_1)/(D_2/b_2)$ is in the range from 0,5 to 1,5 such as from 0,7 to 1,2, such as from 0,8 to 1,0, such as from 0,8 to 0,9. In an embodiment, the elements are holes.

As shown in Fig. 30 in WO03019257, NA scales essentially linearly with λ/b for large b of the air-clad fibres disclosed therein. For small b, however, ($\lambda/b > 1.5$), a deviation from linearity is seen. To compensate for this and to preserve a substantially linear relationship between the product of numerical aperture and core diameter $NA_i{*}D_i$ (and essentially conserve of brightness) over a length of the PCF where cross sectional dimensions are changed, the bridge width b may, for example, be controlled by pressure control during production of the PCF (in the case of decreasing cross sectional dimensions from a first (index i=1) end to a second (index i=2) end, and further decrease b_2 by increasing pressure in the air holes).

For photonic crystal fibres according to the present invention, the most important optical wavelengths are in the ultra-violet to infrared regime (e.g. wavelengths from approximately 150 nm to 11 μm).

In an embodiment of the invention, said core region is homogeneous and made of a single material with refractive index n_{core}.

In a preferred embodiment of the invention, the cross sectional form of the *micro-structural elements* is essentially circular, essentially circular meaning drawn from a preform where the corresponding structural elements have a circular cross section. However, the cross sectional form of the micro-structural elements may take on any appropriate form such as essentially triangular, quadratic, polygonal, elliptical, etc., as implemented by drawing a fibre from a preform having corresponding structural elements of corresponding form(s), possibly modifying the form by proper control of the pressure of capillary preform elements during fabrication cf. the section "A method of manufacturing an NA converting photonic crystal fibre" below. In an embodiment of the invention, the micro-structural elements are holes or voids.

In an embodiment of the invention, 'essentially equal' in connection with cross sectional fibre dimensions (including those of micro-structural elements) is taken to mean that the fibre is drawn from a preform where the corresponding structural elements (typically canes or tubes of circular cross section) have equal outer maximum cross sectional dimension (typically diameter) or inner maximum cross sectional dimension (typically diameter).

In an embodiment of the invention, the (multimode) *core region* is essentially circular in a transversal cross section of the fibre, essentially circular meaning drawn from a preform where the corresponding structural element has a circular cross section, e.g. a circular core cane (hollow or solid) surrounded by a number of circular canes constituting a part of the cladding region.

In an embodiment of the invention, a single- or few-mode inner core is present in the multimode core region. In an embodiment, a PCF having a central core region surrounded by an array of air holes implementing a so-called 'endlessly single-mode' core is provided (i.e. a specially designed microstructured region inside at least part of the multi-mode core may form the cladding of an endlessly single mode fibre; see e.g. WO09900685 for details). Such an optical fibre will be single mode both at the first end (having relatively large cross sectional dimensions) AND at the second end (having relatively small cross sectional dimensions), since the holes are just scaled down (so that the fibre retains single mode properties).

In an embodiment of the invention, the PCF is an optically active fibre. In an embodiment, the PCF comprises an active central core region (so that the NA converting fibre and the active fibre are integrated). This has the advantage of eliminating the need for splicing/coupling light from the NA converting fibre to the active fibre thereby proving practically loss less in-coupling to an active fibre with a small inner cladding.

In an embodiment, the multimode core region of the PCF comprises a rare-earth doped region. In an embodiment of the invention, said core region comprises rare earth dopant ions, such as Er, Yb, Nd, Ho, Sm or Tm or combinations thereof.

In an embodiment of the invention, said core region comprises refractive index modifying, photosensitive and/or optically active dopant material(s), whereby gratings may be written in the fibre and/or the fibre may be used for optical amplification/lasing.

In an embodiment, the PCF is adapted for use as an amplifier or laser. In an embodiment, the PCF comprise one or more reflecting elements. In an embodiment, the PCF comprises at least one Bragg grating. In an embodiment, the PCF comprises a Bragg grating in the second section having the relatively smaller cross sectional dimensions.

The advantage is that the coupling optics may be built into the same optical fibre that provides the gain for a laser or an amplifier. Thereby the need for bulky and lossy bulk optics is eliminated. The integration may also be achieved through splicing of separate (passive) NA converting fibre to separate active double-clad fibres. In an embodiment, the active double clad fibre is a non-air-clad double clad fibre, such as a polymer-based double clad fibre.

<u>A method of manufacturing an NA converting photonic crystal fibre</u>

The present invention also provides a method of manufacturing a PCF, the method comprising the steps of:

a) providing a preform comprising longitudinally extending elements comprising tubes or rods with specific cross sectional dimensions, the preform having a fixed end and a drawing end

b) optionally sealing at least one end of said preform

c) drawing said preform from said drawing end with a predetermined drawing speed in one or more steps including varying said predetermined drawing speed to provide a PCF, having a first end and a second end wherein said first end has cross sectional dimensions that are larger than corresponding cross sectional dimensions of said second end

d) optionally applying a controlled pressure to said fixed end of said preform and optionally varying said applied pressure to control cross sectional dimensions of said drawn PCF.

The fabrication of photonic crystal fibres by drawing from a preform is e.g. discussed by Bjarklev, Broeng and Bjarklev in "Photonic Crystal Fibres", Kluwer Academic Press, 2003 (referred to in the following as [Bjarklev et al.]), chapter 4, pp. 115-130, which is incorporated herein by reference. In particular, the fabrication of air-clad fibres may be performed as described by Broeng et al. in WO03019257 and DiGiovanni et al. in US05907652.

Methods disclosed in the above mentioned references may be adjusted to provide optical components according to the present invention. One

possibility is to adjust the drawing speed during air-clad fibre drawing, such that cross-sectional dimensions of the PCF are varying in the longitudinal direction.

Several optical components according to the invention may be manufactured by drawing PCF from a preform at a first drawing speed v_{d1} (e.g. in the range 1 m/min to 5 m/min) for a certain amount of time t_1 (e.g. 1 to 10 min), and increasing the drawing speed (e.g. a factor of two to four, instantaneously or with a specific rate of change) to a second drawing speed v_{d2}, keeping this speed for a certain amount of time t_2 (e.g. 0.5 to 5 min) and then reducing the drawing speed v_{d2} to the first drawing speed v_{d1}, and then repeating the procedure. By this method several components may be manufactured in a continuous process, thus potentially providing a process suitable for industrial production. The drawn fibre may be cut at appropriate positions to yield a large number of NA converting fibres from a single fibre drawing.

In an embodiment of the invention, the preform design, the drawing temperature T_d, drawing speeds v_{di}, drawing times t_{di}, rate of change of drawing speeds dv_{di}/dt, and the optionally applied pressure P to the fixed end of the preform for controlling the hole dimensions are optimized to achieve that the ratio of the maximum cross sectional dimension of the multimode core region to the minimum boundary to boundary distance between neighbouring elements of a ring of elements of the air-clad of the drawn PCF, D_i/b_i is substantially equal at the cross sections of the first and second ends of the PCF. In an embodiment, the ratio $(D_1/b_1)/(D_2/b_2)$ is in the range from 0,5 to 1,5 such as from 0,8 to 1,2, such as from 0,9 to 1,1.

In an embodiment, the tapering of the PCF (i.e. change of the maximum cross sectional dimension of the multimode core region) occurs over a length of the PCF in the range of 0.1 m to 10 m, such as over 0.2 m to 5 m, such as over 0.5 m to 0.1 m.

<u>An article comprising an NA converting photonic crystal fibre</u>

An article comprising a photonic crystal fibre as discussed in section "An NA converting photonic crystal fibre" above, in the detailed description and as defined in the corresponding claims is furthermore provided by the present invention, whereby improved devices performing specific functions such as lasers or amplifiers can be provided.

In an embodiment of the invention, the article is a fibre laser.

In an embodiment of the invention, the article is a fibre amplifier.

In an embodiment, the article is a fibre laser sub-assembly. In an embodiment, the article is a fibre amplifier sub-assembly.

Use of an NA converting photonic crystal fibre

Use of a photonic crystal fibre as discussed in section "An NA converting photonic crystal fibre" above, in the detailed description and as defined in the corresponding claims is furthermore provided by the present invention, whereby specific functional features can be achieved in a relatively simple and economic way.

In embodiments of the invention, use is made of a PCF according to the invention in a fibre amplifier or in a fibre laser.

Further objects of the invention are achieved by the embodiments defined in the dependent claims and in the detailed description of the invention.

It should be emphasized that the term "comprises/comprising" when used in this specification is taken to specify the presence of stated features, integers, steps or components but does not preclude the presence or addition of one or more other stated features, integers, steps, components or groups thereof.

BRIEF DESCRIPTION OF DRAWINGS

The invention will be explained more fully below in connection with a preferred embodiment and with reference to the drawings in which:

Fig. 1 shows a schematic drawing of an optical component according to the invention;

Fig. 2 shows a schematic illustration of a cross-section of a first end of a photonic crystal fibre;

Fig. 3 shows the measured NA, core diameter and losses of a photonic crystal fibre according to an embodiment of the present invention attenuation as function of fibre length;

Fig. 4 shows the NA conversion from one end to another end of a photonic crystal fibre according to an embodiment of the present invention;

Fig. 5 shows measured NA as function of core size of a photonic crystal fibre according to an embodiment of the present invention;

Fig. 6 schematically shows a prior art a lens system to couple light from one optical fibre to another;

Fig. 7 schematically shows elements of an article according to the invention;

Fig. 8 shows an article according to the invention in the form of a laser; and

Fig. 9 shows an article according to the invention in the form of a coupler.

Fig. 10a and b show cross-sections of a large end and small end, respectively, of an optical fibre according to the invention.

The figures are schematic and simplified for clarity, and they just show details, which are essential to the understanding of the invention, while other details are left out.

MODE(S) FOR CARRYING OUT THE INVENTION

Optical components according to the present invention are typically in the form of optical fibre, i.e. flexible light guiding devices. The optical fibres have a longitudinal direction and a cross-section perpendicular thereto. The optical fibre comprises a number of longitudinally extending features that may vary in cross-sectional size along the fibre (a photonic crystal fibre). The variation is in the form of a tapering, providing larger cross sectional feature dimensions in a first fibre end than in a second fibre end. The optical fibre comprises an air-clad. An air-clad is in the present context taken to mean a cladding region comprising holes or voids that surrounds a multi-mode core. As the dimensions of the air-clad are reduced as the fibre is tapered down, the NA of the optical fibre is increased. This is used to provide coupling of light from a large spot/core size and a low NA to a small spot/core size with a high NA.

Most references to physical fibre parameters - such as dimensions – and figures of fibre designs refer to or illustrate a photonic crystal fibre cross-section.

One preferred embodiment of a photonic crystal fibre according to the present invention is shown schematically in Fig. 1, the photonic crystal fibre having first and second ends or end faces 11, 12. The figure shows a schematic design of a tapered air-clad fibre (TAF). The TAF has a core 2, 6 (typically a core supporting multiple modes – the core being referred to as a multi-mode core). The TAF is characterized by a first section 3 with a relatively large core dimension 20 and second section 5 with a relatively smaller core dimension 60. The difference in core size is a result of a tapered section 4. Light may be confined and guided in the multi-mode core using a ring of holes 1 (referred to as air-clad). The air-clad may extend through the full fibre length or through a majority of the fibre length.

The fibre may for example comprise sealed end facets as e.g. described by Skovgaard et al. in WO03032039. Over the length of section 3 the fibre has a large diameter and it is longitudinally uniform, the length of section 3 being arbitrary. Section 4 is a tapered section where the cross sectional diameter of the photonic crystal fibre is reduced from the relatively large diameter in section 3 to the relatively small diameter of section 5. In section 5 the fibre has a relatively small diameter and is longitudinally uniform, the length of section 5 being arbitrary. The tapered section 4 may extend over any convenient length with a view to the light guiding properties of the section. The length of tapered section 4 may e.g. be in the range from 0.5 m to 5 meter, such as from 1 to 3 m.

The fibre in Fig. 1 will typically be used in an application where light is coupled to the core at the first end 11 (for example directly from a laser diode array or from a second optical fibre) with a low NA (typically NA in the range from 0.1 to 0.5) and transmitted through the photonic crystal fibre to the second end 12 with a relatively smaller core 6 and an increased NA. The second end 12 may for example be spliced or butt-coupled to another air-clad fibre, typically an air-clad fibre with a single- or few-mode, rare earth doped core (see e.g. WO03019257). Light may also be coupled between such two fibres using bulk optics. Alternatively, the TAF itself may comprise a rare-earth doped core. Typically, a single- or few mode core is embedded in the multi-mode core (not shown in the figure for reasons of clarity). The TAF may also comprise a passive single- or few mode core. Optionally, the single- or few mode core may comprise UV-sensitive material(s) such that e.g. gratings may be written in the fibre. In this respect, the photonic crystal fibre could be used as a component combining coupling, gratings, and/or gain material.

Fig. 2 shows a schematic cross section of an end – or end facet 21 - of a photonic crystal fibre realized according to a preferred embodiment of the present invention. The fibre is preferably made from silica. The fibre comprises a ring of holes 22 – the air-clad 23. The holes are separated by bridge 24 of solid material (e.g. silica). In the schematic cross section of the fibre of Fig. 2, the width b of the bridge between two neighbouring holes (being defined as the minimum spacing between the outer

boundaries said two neighbouring holes of the air-clad) is shown to be essentially constant in a radial direction of the fibre and to be essentially equal for all holes 22 of the air-clad 23. This is preferred but not essential. The bridge for any given neighbouring pair of holes in the air-clad may have a varying width in a radial direction of the fibre, e.g. steadily increasing or irregular (reflecting different cross sectional forms of the holes, including irregularities due to manufacturing tolerances leading to feature forms deviating from ideality/and or intention). Preferably, the holes 22 are air-filled. Outside the air-clad a solid region of silica is placed, the so-called outer cladding 24 that provides mechanical strength and protection of the fibre. Various types of coatings may be applied to the fibre. The region within the ring of air holes is termed the multi-mode core 25 (sometimes also referred to as pump core or inner cladding). Because of the low effective index of the air-clad 23, and a relatively large cross sectional dimension (here diameter), D, of the core, the core 25 (and air-clad 23) may form a multi-mode waveguide with a given NA. The value of the NA depends on the parameter b, as described in details in WO03019257. Hence, the multi-mode core may guide light with a given brightness, e.g. launched from a multimode laser pump diode. As the fibre is tapered down along its length, the parameters D and b are decreased in absolute dimensions. This provides an increased NA and decreased cross sectional core dimension (cf. 60 in Fig. 1). In a preferred embodiment, the photonic crystal fibre has a substantially constant ratio of b and D throughout the length of the photonic crystal fibre, in order to convert the NA while reducing the core/spot size. This may e.g. be achieved by linear dimension scaling through the tapered section (cf. 4 in Fig. 1). The b/D ratio may alternatively be varied along the length to provide further flexibility for converting NA and core/spot size. This may for example been obtained by applying a pressure to the holes forming the air-clad during drawing. The tapering is preferably performed during drawing of the fibre.

In another preferred embodiment of the fibre, the core or parts thereof is doped with rare earth ions, such as Er, Yb, Nd, Ho, Sm or Tm.

Fig. 3 shows experimental results from a TAF according to the present invention. In this experiment a 9 m long TAF was used. The large core

end has a core diameter of 400 μm at the relatively large end (see numeral 20 in Fig. 1) and a core diameter of 190 μm at the relatively small end (see numeral 60 in Fig. 1). The lengths of first, tapered and second sections 3, 4 and 5 in Fig. 1 were 3 m, 3 m, and 3 m respectively. During the drawing process where the tapering took place, the ratio between core sizes, D, and the width of the bridges between holes, b (see Fig. 2) were kept constant to within production accuracy by adjusting only drawing speed while keeping other drawing parameters as constant as possible (including furnace temperature, preform feeding speed, pressure in holes, etc.). In the experiment, light was launched from the large core end (11 in Fig. 1) and the fibre was cut, seven times, from the other end (12 in Fig. 1) and data recorded for each cut.

In the top diagram of Fig. 3 the solid circles represent the measured diameter of the core (cf. left hand vertical axis denoted 'Core Diameter [μm]') as a function of distance from the first end face 11 to the second end face 12 of the photonic crystal fibre (cf. Fig. 1) (cf. horizontal axis denoted 'Length of fiber [m]'), and the squares represent the measured numerical aperture (cf. right hand vertical axis denoted 'NA'), as a function of said distance. The graph shows that there is a relation between reduced core size and increased numerical aperture that provides NA conversion for changed core/spot size.

In the lower diagram in Fig. 3 the optical loss of the photonic crystal fibre (cf. left hand vertical axis denoted 'Loss [db]') is plotted as a function of length of the photonic crystal fibre from the first end face 11 to the second end face 12 of the photonic crystal fibre (cf. Fig. 1). A comparison of loss (lower diagram) with the diameter of the core (top diagram) shows that there is no significant relation between loss and variations of core dimensions (as there are no abrupt or dramatic changes for the loss over the tapered section compared to the untapered sections). Further it can be seen that the loss in the tapered region (over the length of around 3 m), for this device, is approximately 1.5 dB. Such a loss level is comparable or low compared to what can be obtained using bulk optics for NA conversion and spot size reduction, In particular this is low for NA conversion up to around 0.50 or higher. Hence, the TAF provides a fibre-

based alternative to bulk optical devices. A fibre-based alternative is attractive for many reasons; including reduced cost, improved connectivity to other optical fibres/fibre-based components, improved mechanical stability, and many more.

It is important to notice that the increase in NA as the core is decreased cannot be obtained using a conventional (non-micro-structured) double clad fibre. For conventional double clad fibres, NA is determined by absolute refractive index differences between a high-index, multi-mode core and a low-index cladding formed typically using low-index polymer. Tapering down the size of such a conventional fibre would reduce the core/spot size, but leave the NA unchanged (as the polymer does not change its refractive index). Hence the brightness would not be conserved for a conventional fibre, as is possible by preferred embodiments of the present invention.

Fig. 4 shows relationship between launched NA and transmitted NA (Launched NA and transmitted NA being numerical aperture at first 11 and second ends 12, respectively, of a photonic crystal fibre according to preferred embodiments of the present invention (cf. Fig. 1)). The graph in Fig. 4 demonstrates that the fibre can be operated bidirectionally. The fibre used in this experiment is the full length of the fibre used for the data in Fig. 3. The solid squares show the numerical aperture when launching light into the relatively small core (numeral 6 in Fig. 1) as a function of the detected numerical aperture in the large core (numeral 2 in Fig. 1). The solid circles show the numerical aperture when light is launched into the large core (numeral 2 in Fig. 1) as a function of the detected numerical aperture in the small core (numeral 6 in Fig. 1). From the overlap of the data points it can be deduced that the fibre is bidirectional and that it linearly transform from one numerical aperture to another.

The diagram in Fig. 5 shows relationship between numerical aperture and core diameter. The solid squares represent experimental data from the top graph in Fig. 3 (solid squares also in Fig. 3, top). The stapled line represents the calculated numerical aperture for different core sizes where the ratio between core size, D, and bridge width, b, is kept constant, i.e.

the structure scales linearly. For the calculation of numerical aperture from the bridge width the empirical formula in WO03019257 (Fig. 30) is used. The bridge width is 400 nm for the 200 μm core. The experimental data confirms that the structure dimensions scale linearly through the tapered section.

The solid line represents conservation of luminance, with a fixed point at the small core end (numeral 12 in Fig. 1). The behaviour of this particular fibre can be deduced from this graph. If light is launched into the small end with maximum NA, all light will be transmitted through the fibre. However, when light is launched from the large core size end, this fibre does not support the increase of NA required for conservation of brightness and only light with NA supported by the small end is guided – a fraction of the light is therefore lost. It is desired to keep this loss as low as possible. This may, for example, be obtained by decreasing the b dimensions slightly more than the dimensional downscaling of D. In other words, to increase the D/b ratio slightly over the tapered section (4 in Fig. 1) from large to small core size. This may, for example, be achieved by applying an increased pressure to the holes during drawing when the drawing speed is increased to taper down the fibre.

It may, however, in some cases be an advantage that a small fraction of the light is lost. Considering a device used to pump a double clad fibre; the advantage is that if light emitted from a pump diode is not well defined, the dumping of energy that is not within a specified NA can be done along the length of the tapered fibre and thus not lose all energy at one point. Hence, physical damage from dumping high excess powers at spatially narrow positions may be avoided. Therefore, preferred embodiments of the present invention may be used to obtain high power devices with well-defined NA and spot sizes (the NA and core size being determined from the small end).

Fig. 6 schematically shows a prior art lens system to couple light from one optical fibre to another wherein light 1902 originating from a high power semiconductor laser pigtailed to a standard (i.e. non-micro-structured, solid glass) MM fibre 1903 is coupled to a double clad fibre 1904 via bulk

optics in the form of lens system 1901. A PCF according to the present invention may substitute the lens system 1901 as indicated on Fig. 7. This shows schematically elements of an article according to the invention. In Fig. 7a, lens system 1901 of Fig. 6 is substituted by the tapered PCF 4, and elements 3 and 5 corresponding to multimode fibre 1903 (providing pump light) and double clad fibre 1904 (e.g. being part of a fibre laser or amplifier) of Fig. 6. The multimode fibre 1903 may alternatively be a laser diode, a laser diode array, a lens system or any other component or device feeding pump light to the tapered PCF 4. The component 1904 may or may not be in contact with the tapered fibre 4 (splices, butt-couplings, lens-couplings, etc may be imagined). Fig. 7b schematically indicates an article according to the invention wherein the tapered PCF and the double clad fibre (e.g. for implementing a laser or amplifier) are integrated into one component (PCF) 45, thereby avoiding losses due to coupling/splicing between the corresponding discrete elements (4 and 5 in Fig. 6).

Fig. 8 shows an article according to the invention in the form of a fibre laser 81, comprising a section of a tapered PCF 4 having a multimode core region comprising a centrally located doped core, which at a first end is slightly multimode (MM) and at a second end is single mode (SM). A first reflecting M1 element is located at the first end of the PCF having a relatively large cross sectional dimension and a second reflecting element M2 is located at the second end having a relatively smaller cross sectional dimension. The reflecting element(s) may be fibre Bragg gratings, external reflectors, end-facet reflectors, etc. The component is optically coupled at its first end from a multimode pump source 3 (e.g. an array of laser diodes possibly coupled directly into the PCF 4 or via an appropriate optical waveguide) and at its second end optically coupled (e.g. butt-coupled) or integrated with (i.e. being part of the same optical waveguide) to a fibre laser. The following relation is substantially fulfilled for the cross sections of the first and second ends of the PCF:

$$D_{core,1} / D_{MM\ core,1} = D_{core,2} / D_{MM\ core,2}$$

The multimode core dimension ($D_{MM\ core,i}$) corresponds to the parameter D of Fig. 2 as given at said first (i=1) and second (i=2) ends of the tapered PCF 4. $D_{core,i}$ indicates the cross sectional dimension of the doped core at the first and second ends, i=1, 2, respectively.

At the pump end (first end) $D_{MM\ core}$ is relatively large, allowing efficient, easy pump coupling, but absorption is the same as at the second end, while retaining single mode output. One or both of the reflecting elements 82 may e.g. be implemented as fibre Bragg gratings.

Fig. 9 shows an optical component according to the invention in the form of an optical coupler, comprising sections of a tapered PCF (comprising an up- as well as a down-tapering) having a multimode core region (denoted 'MM core' in Fig. 9) and comprising a centrally located doped core. The fibre may be side-pumped (see e.g. WO03079077 for details of side-pumping air-clad fibre) at one or more positions. Preferably, the side pumping is performed at positions of larger dimensions. The larger dimensions may be advantageous positions for the side pumping due to easier handling, larger volumes of glass to receive (high) optical power. Hence, the enlargement of the inner-clad cross-section in the coupling region may lead to an increased coupling efficiency and better power handling, thereby facilitating coupler fabrication.

Fig. 10a and b show microscope photographs of cross-sections of a large end and small end, respectively, of an optical fibre according to the invention. The photographs are of the optical fibre that the measurements in Fig. 3, 4, and 5 are for. Fig. 10a shows the large end recorded using 10x microscope objective lens, and Fig. 10b shows the small end recorded using 20x microscope objective lens. Slight damage on one side (lower left side) of each fibre is seen due to bad cleaving.

THE PRODUCTION PROCESS

Various aspects of manufacturing a photonic crystal fibre including the preparation of a preform is discussed in chapter 4 in [Bjarklev et al.].

The invention is defined by the features of the independent claim(s). Preferred embodiments are defined in the dependent claims.

Some preferred embodiments have been shown in the foregoing, but it should be stressed that the invention is not limited to these, but may be embodied in other ways within the subject-matter defined in the following claims.

CLAIMS

1. A photonic crystal fibre comprising

a) a multi-mode core region for propagating light in a longitudinal direction of said photonic crystal fibre,

b) an air-clad region comprising a multitude of longitudinally extending spaced apart micro-structural elements surrounding said multi-mode core region,

the photonic crystal fibre comprising a first and a second end, wherein cross-sectional dimensions of said multimode core region and said air-clad region are reduced from said first end to said second end so that brightness is essentially conserved.

2. A photonic crystal fibre according to claim 1 wherein said cross sectional dimensions of the multimode core region and the air-clad region are smaller at said second end than at said first and whereby it is achieved that the PCF has a larger numerical aperture at said second end than at said first end.

3. A photonic crystal fibre according to claim 1 or 2 wherein the numerical aperture NA and maximum cross sectional dimension D of the multimode core region at said first and second ends NA_1, D_1 and NA_2, D_2, respectively, are adapted so that ratio NA_1*D_1/NA_2*D_2 is in the range from 0,5 to 1,5 such as from 0,8 to 1,2, such as from 0,9 to 1,1.

4. A photonic crystal fibre according to any one of claims 1-3 wherein said air-clad comprises at least one ring of longitudinally extending micro-structural elements.

5. A photonic crystal fibre according to claim 4 wherein the minimum boundary to boundary distance b between neighbouring micro-structural elements of the air-clad in an annular direction is substantially constant for all elements of a particular ring.

6. A photonic crystal fibre according to claim 4 or 5 wherein the ratio D/b of the maximum cross sectional dimension of the multimode core region D

to the minimum boundary to boundary distance b between neighbouring elements of a ring of elements of said air-clad, is substantially equal at the cross sections of said first and second ends of the PCF.

7. A photonic crystal fibre according to claim 6 wherein the ratio $(D_1/b_1)/(D_2/b_2)$ of the ratio D/b at said first and second ends, is in the range from 0,5 to 1,5 such as from 0,7 to 1,2, such as from 0,8 to 1,0, such as from 0,8 to 0,9.

8. A photonic crystal fibre according to any of the preceding claims wherein said multimode core region is homogeneous and made of a single material with refractive index $n_{MM\ core}$.

9. A photonic crystal fibre according to any of the preceding claims wherein said multimode core region comprises a single mode or few-mode core region.

10. A photonic crystal fibre according to claim 9 wherein said single mode or few-mode core region is homogeneous and made of a single material with refractive index $n_{SM\ core}$ and/or said single mode or few-mode core region comprises optically active material, such as one or more rare-earths.

11. A photonic crystal fibre according to any of the preceding claims wherein at least some of said micro-structural elements are holes or voids.

12. A photonic crystal fibre according to any of the preceding claims wherein said multimode core region comprises a core region surrounded by an array of air holes or voids.

13. A photonic crystal fibre according to any of the preceding claims wherein said PCF comprises refractive index modifying, photosensitive and/or optically active dopant material(s).

14. A photonic crystal fibre according to any of the preceding claims wherein said PCF comprises one or more optically reflecting elements such as one or more Bragg gratings.

15. A photonic crystal fibre according to any of the preceding claims wherein said PCF comprises a rare-earth doped region, comprising rare earth dopant ions selected from the group comprising Er, Yb, Nd, Ho, Sm or Tm and combinations thereof.

16. A photonic crystal fibre according to any of the preceding claims wherein the photonic crystal fibre is adapted to guide light comprising a wavelength in the ultra-violet to infrared regime.

17. A method of manufacturing a photonic crystal fibre, the method comprising the steps of:
a) providing a preform comprising longitudinally extending elements comprising tubes or rods with specific cross sectional dimensions, the preform having a fixed end and a drawing end
b) optionally sealing at least one end of said preform
c) drawing said preform from said drawing end with a predetermined drawing speed in one or more steps including varying said predetermined drawing speed to provide a PCF, having a first end and a second end wherein said first end has cross sectional dimensions that are larger than corresponding cross sectional dimensions of said second end.
d) optionally applying a controlled pressure to said fixed end of said preform and optionally varying said applied pressure to control cross sectional dimensions of said drawn PCF

18. An article comprising a photonic crystal fibre according to any onoe of claims 1-16.

19. Use of a photonic crystal fibre according to any one of claims 1-16.

NUMERICAL APERTURE CONVERTING DEVICE, METHOD OF ITS PRODUCTION, AND USE THEREOF

ABSTRACT

The invention relates to a photonic crystal fibre comprising a) a multi-mode core region for propagating light in a longitudinal direction of said photonic crystal fibre, b) an air-clad region comprising a multitude of longitudinally extending spaced apart micro-structural elements surrounding said multi-mode core region, the photonic crystal fibre comprising a first and a second end, wherein cross-sectional dimensions of said multimode core region and said air-clad region are reduced from said first end to said second end so that brightness is essentially conserved. The invention further relates to a method of manufacturing a photonic crystal fibre, an article comprising and the use of such photonic crystal fibre. The invention may be used in applications such as fibre lasers or amplifiers, where light may be coupled efficiently from pump sources to a double clad fibre using the NA converting photonic crystal fibre.

(Fig. 1 should be published)

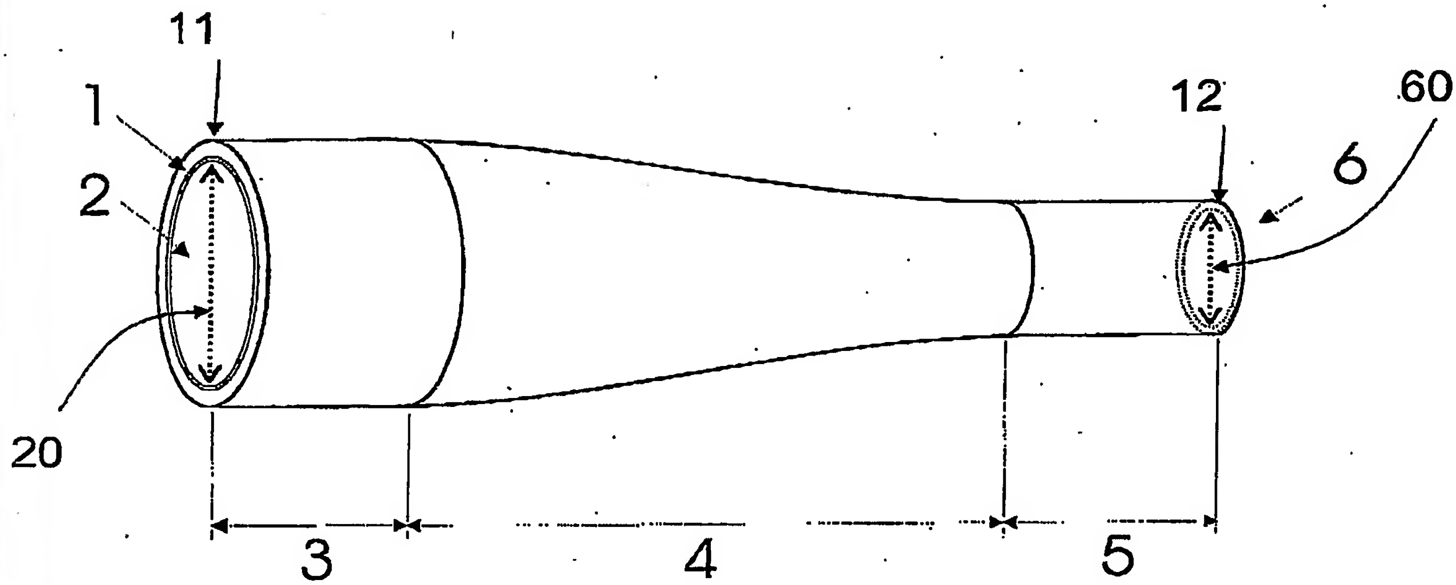

Fig. 1

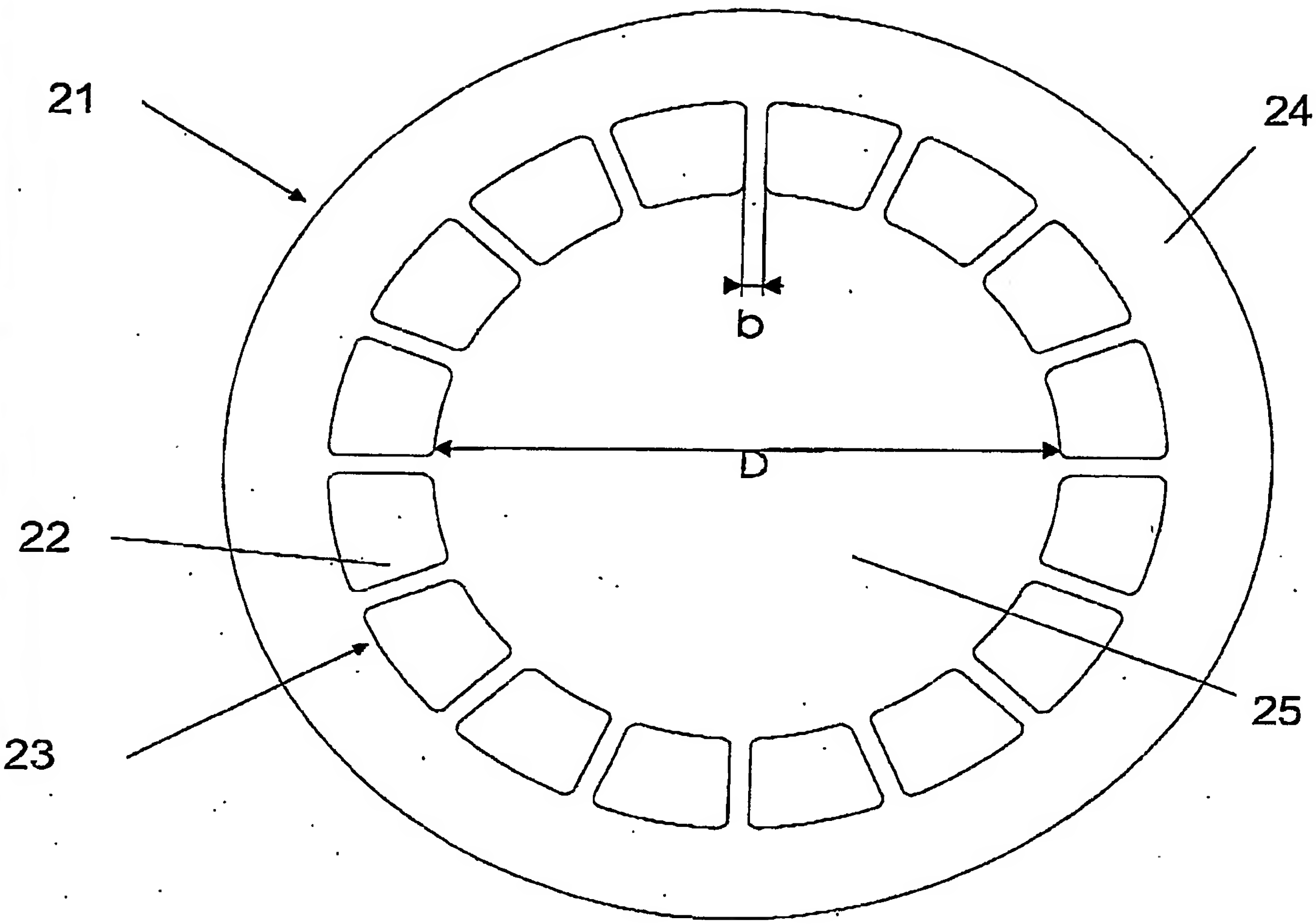

Fig.2

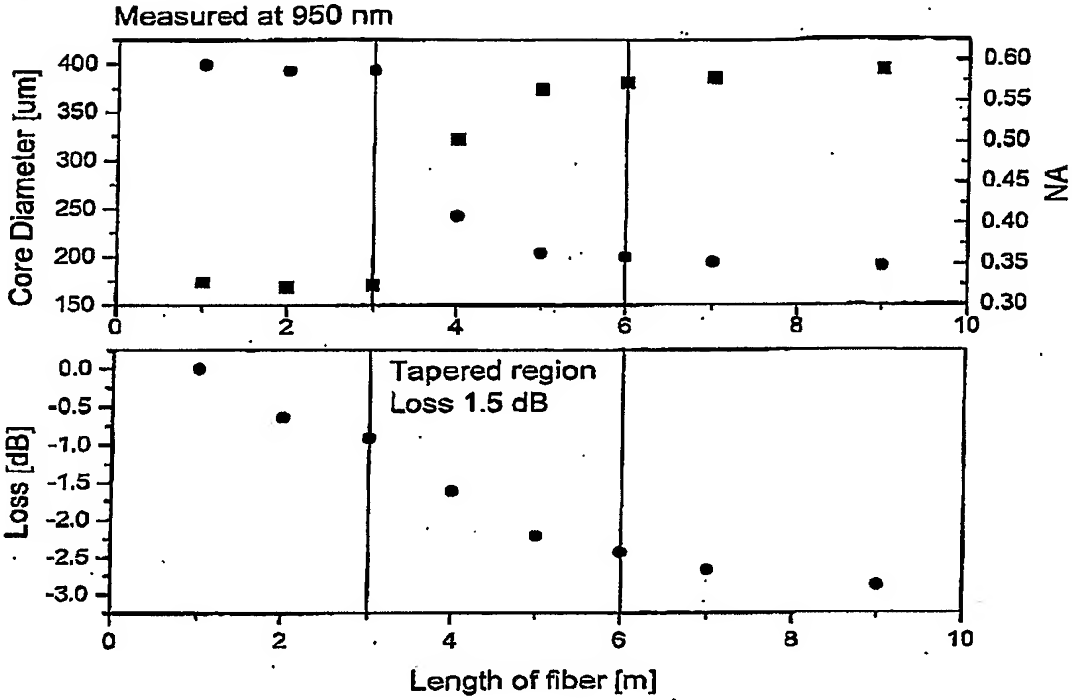
Measured at 950 nm
Core Diameter [um]
400
350
300
250
200
150
0.60
0.55
0.50
0.45
0.40
0.35
0.30
NA
0
2
4
6
8
10
Tapered region
Loss 1.5 dB
Loss [dB]
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
Length of fiber [m]

Fig. 3

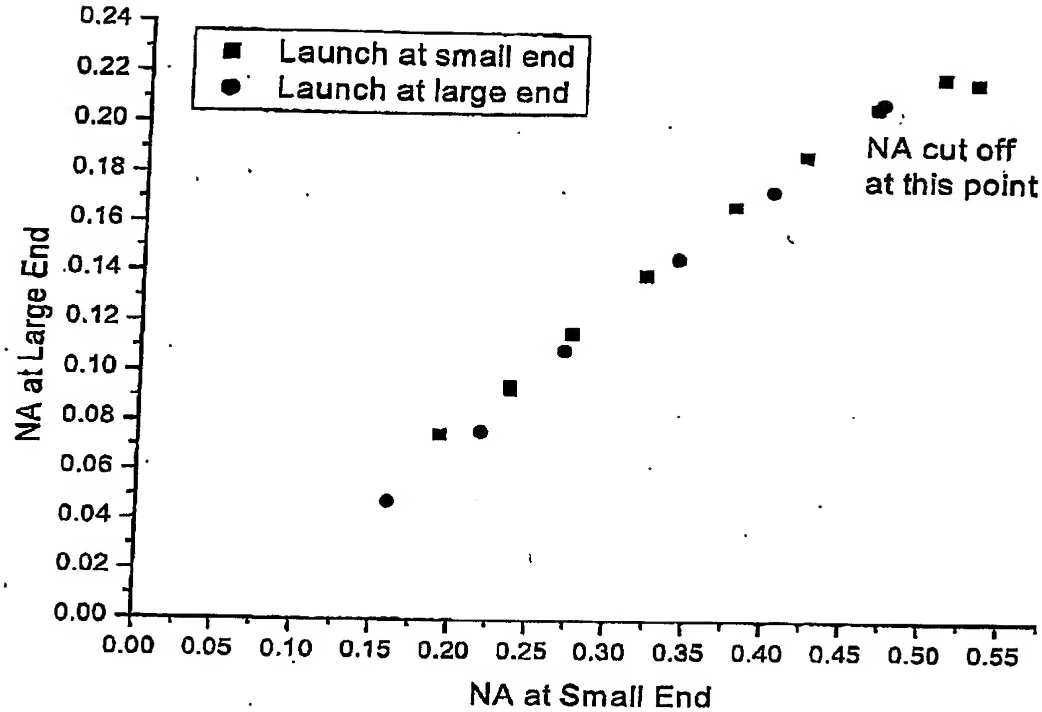
Launch at small end
Launch at large end
NA cut off at this point
NA at Large End
NA at Small End
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55

Fig. 4

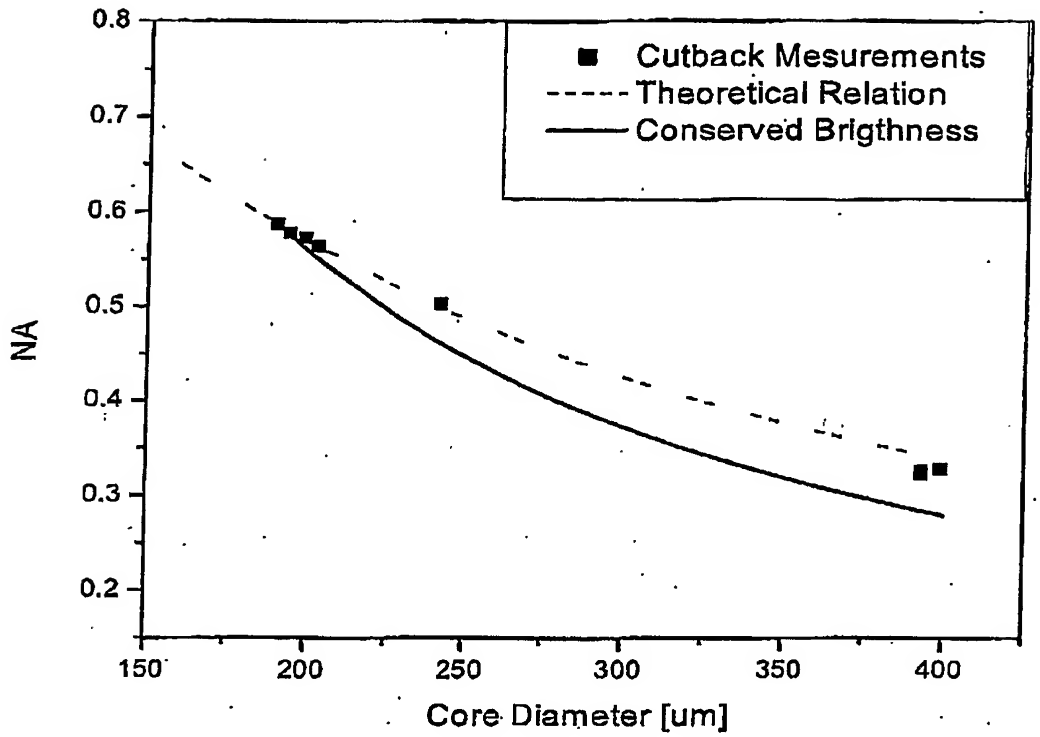
Cutback Mesurements
Theoretical Relation
Conserved Brigthness
NA
0.8
0.7
0.6
0.5
0.4
0.3
0.2
150
200
250
300
350
400
Core Diameter [um]

Fig. 5

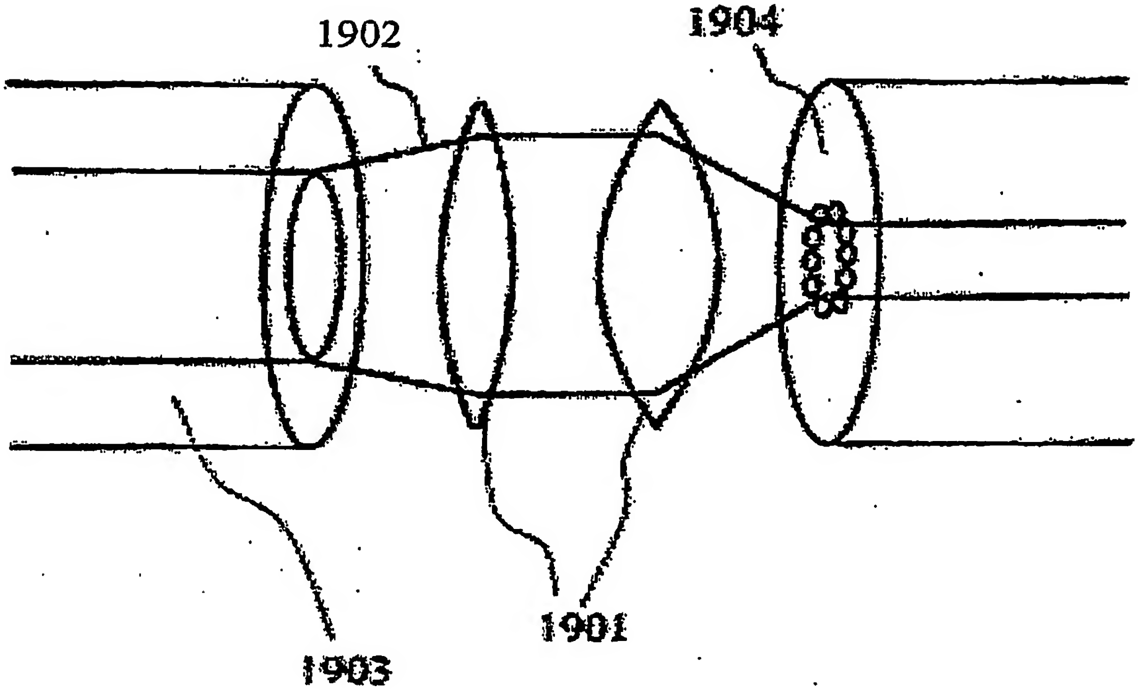

Fig. 6

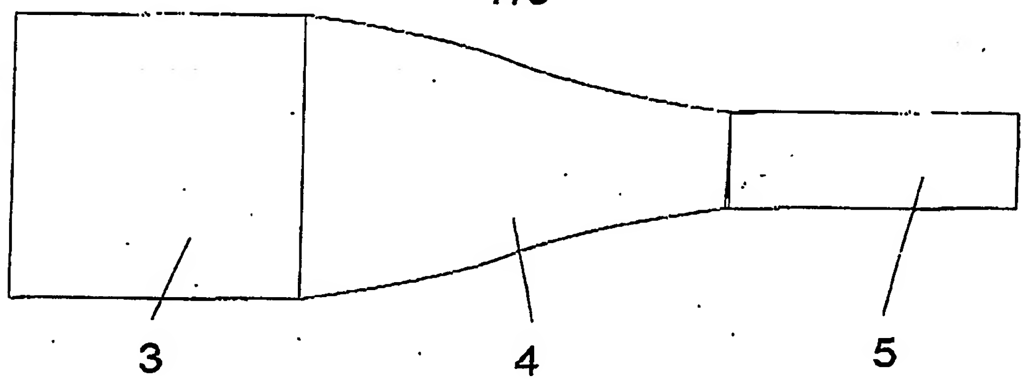

Fig. 7a

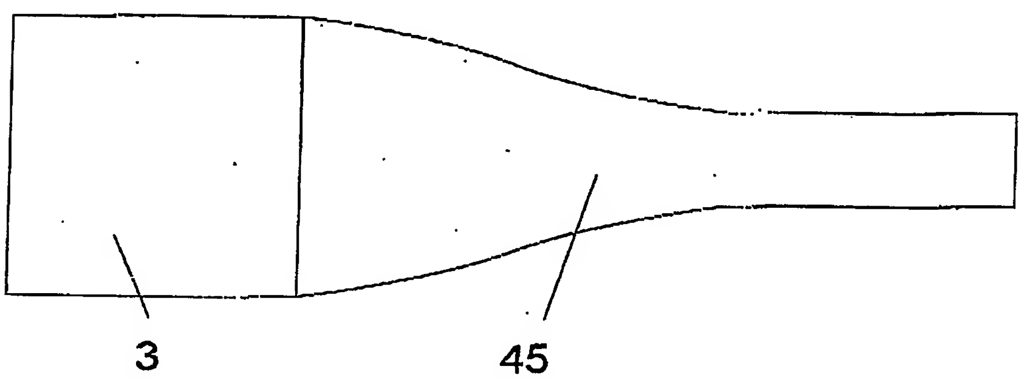

Fig. 7b

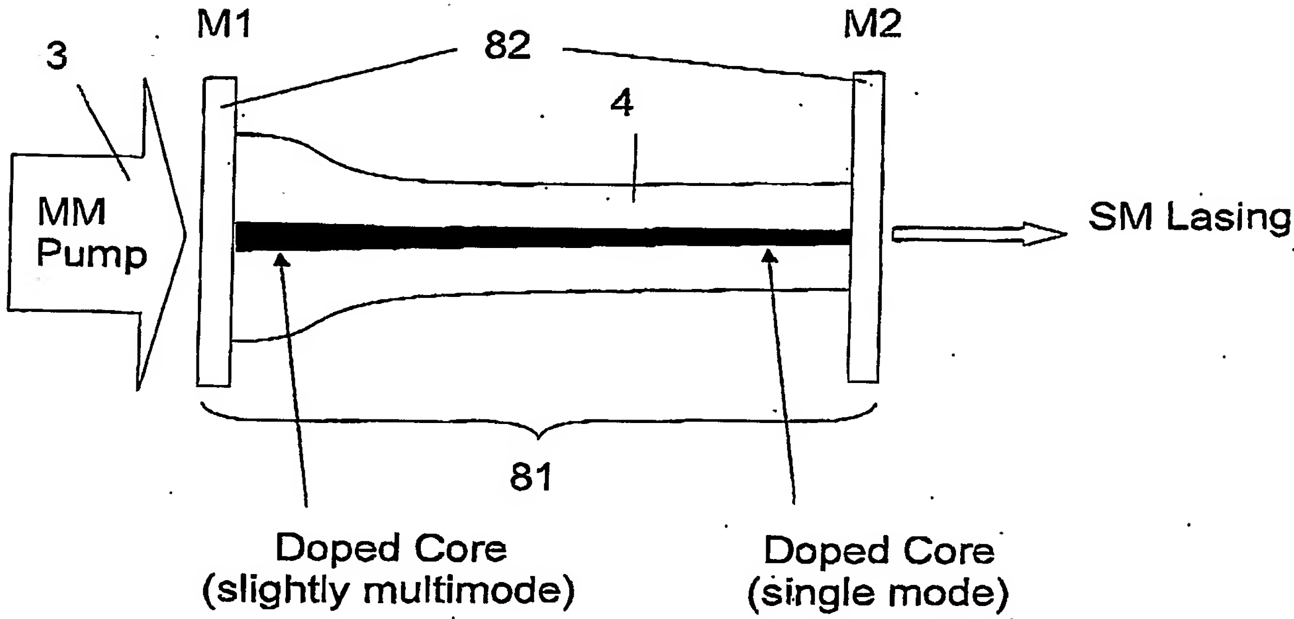
M1
M2
3
82
4
MM
Pump
SM Lasing
81
Doped Core
(slightly multimode)
Doped Core
(single mode)

Fig. 8

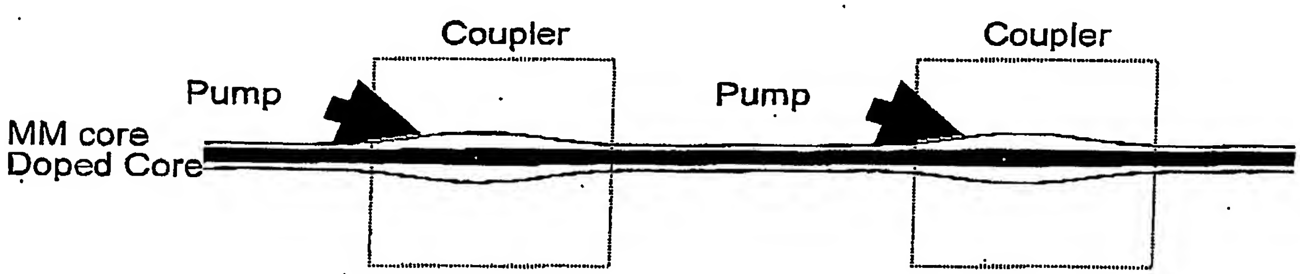
Coupler
Coupler
Pump
Pump
MM core
Doped Core

Fig. 9

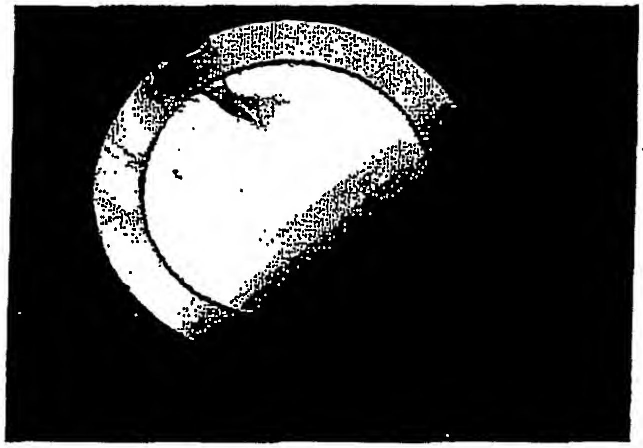

Fig. 10a

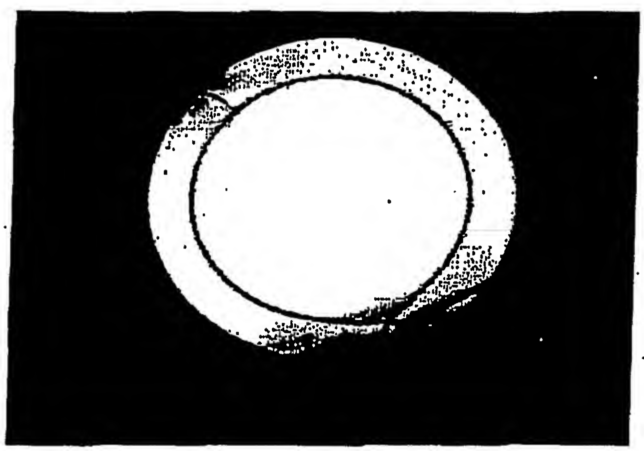

Fig. 10b